The charm of hot matter - charmonium and open charm measurements in Pb–Pb collisions with ALICE at the LHC

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Abstract. We present selected results obtained by the ALICE Collaboration concerning charmed hadron and quarkonium production in Pb–Pb collisions at the LHC.

1. Introduction

The goal of high-energy nucleus-nucleus collisions is to produce and characterize a state of nuclear (QCD) matter at (energy) densities well above the nuclear ground state ($\varepsilon_0 \simeq$0.15 GeV/fm^3). At high densities and/or at high temperatures one expects [1, 2] that quarks are no longer confined in protons and neutrons but move freely over distances larger than the size of the nucleon ($\simeq$1 fm=10^{-15} m). Employing Quantum Chromo-Dynamics calculations on a space-time lattice, a deconfinement phase transition for an energy density of about 1 GeV/fm^3 was predicted (see [3] for an early review). The characterization of quark-gluon matter in terms of its equation of state (EoS, relating pressure to energy) and of its transport properties (such as viscosity) and delineating its phase diagram is a major ongoing research effort in collisions of nuclei at high energies.

Heavy quarks (charm and bottom) are a prominent part of the so-called “hard probes”, observables characterized by an energy (mass) scale much larger than the temperature of the deconfined medium (of a few hundred MeV). These observables are produced in primary hard scattering processes and their yields are calculable in elementary hadronic collisions with perturbative QCD techniques [4, 5, 6, 7]. The production of hard probes in nucleus-nucleus (AA) collisions is quantified by the nuclear modification factor: $R_{\mathrm{AA}} = \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \cdot \mathrm{d}^2 N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$, where $\mathrm{d}^2N/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y$ denotes the transverse momentum (p_{T}) and rapidity (y) differential yield of a given observable measured in AA or pp collisions and $\langle N_{\mathrm{coll}}\rangle$ is the average number of nucleon-nucleon collisions over the given centrality interval of AA collisions; $\langle N_{\mathrm{coll}}\rangle$ is calculated using the Glauber model [8]. Also calculated within this geometric model is the number of participating nucleons, $\langle N_{\mathrm{part}}\rangle$, used in the following for study of centrality dependence of R_{AA}.

The p_{T} spectra of hadrons carrying light quarks and their azimuthal distributions with respect to the reaction plane (defined by the beam axis and the impact parameter of the colliding nuclei) exhibit features of collective flow and are described well by hydrodynamical models (see a recent review in [9]). In non-central collisions, the initial approximately elliptic shape (in the transverse plane) of the overlap zone of the colliding nuclei leads, through the initial gradients of the energy

density (or pressure), to anisotropic spatial (azimuthal angular) emission of hadrons. This is quantified by the second order (quadrupole) Fourier coefficient $v_2 = \langle \cos(2\phi) \rangle$, where ϕ is the azimuthal angle with respect to the reaction plane.

The study of (deconfined) QCD matter has entered a new era in year 2010 with the advent of Pb–Pb collisions at the Large Hadron Collider (LHC), delivering the largest ever collision energy, $\sqrt{s_{\mathrm{NN}}}$=2.76 TeV, more than a factor of 10 larger than previously available. We present selected results obtained by the ALICE Collaboration concerning charmed hadron and quarkonium production. The ALICE detector is described in [10]. The results presented below correspond to minimum-bias Pb-Pb run of the year 2010 and to the high-statistics Pb-Pb run of the year 2011. An integrated luminosity $L_{int} \simeq$30 μb^{-1} was collected in 2011 with centrality triggers for the ALICE Central Barrel at midrapidity ($|y| < 0.9$), while $L_{int} \simeq$70 μb^{-1} was collected with (di)muon triggers in the forward Muon Spectrometer ($2.5 < y < 4$).

2. Open charm hadrons

Produced very early in the collision, at times $t \simeq 1/2m_q$, heavy quarks experience the full evolution of the hot fireball of partons. At variance with light quarks, which can be thermally produced, heavy quarks maintain their identity through the hot stage of the collision. They help to address the question if parton energy loss (by gluon radiation) exhibits the expected quark mass pattern. The theoretical expectation is that heavy quarks (charm and bottom) lose less energy (by gluon radiation) compared to lighter (up, down, strange) quarks [11]. The related question, often asked, is whether heavy quarks thermalize alongside the light quarks and gluons. The measurements at the LHC were eagerly awaited in order to establish in a new energy regime the observation at RHIC, at a center of mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, of heavy quark energy loss and collective flow [12].

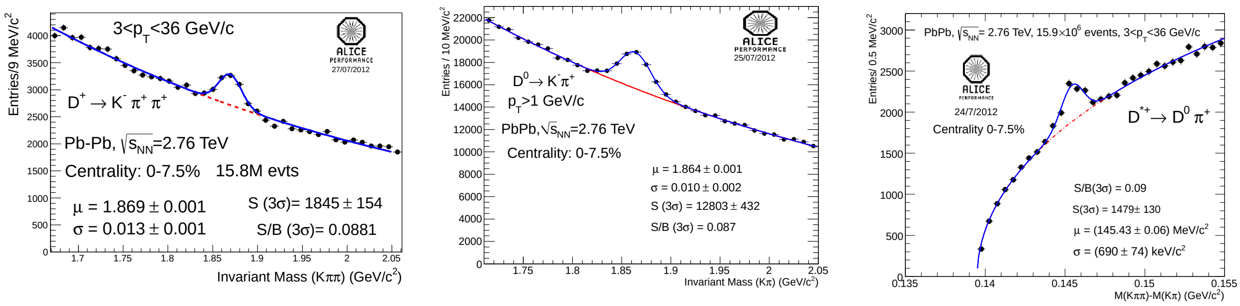

Figure 1. Invariant mass distributions for charmed meson candidates for central (0-7.5% centrality) Pb-Pb collisions. Particles and antiparticles are included.

The production of hadrons carrying open charm is studied in ALICE via the direct reconstruction of hadronic decays [13] at midrapidity, $|y| < 0.5$, and via the measurement of decay electrons [14] (at midrapidity) or muons [15] (at forward rapidity, $2.5 < y < 4$). Invariant mass distributions for charmed meson candidates are shown in Fig. 1 for central (0-7.5% centrality) Pb-Pb collisions. Owing to the very good resolution of track impact parameter in the transverse plane (65 μm for $p_{\mathrm{T}} = 1$ GeV/c and reaching asymptotically 20 μm) and to the good hadron identification performance, a very good signal to background ratio S/B of about 10% is reached for various D-meson species. The very good momentum resolution of ALICE at low p_{T} leads to invariant mass resolutions around 10 MeV/c^2 for the D$^+$ and D^0 mesons.

The transverse momentum dependence of the nuclear modification factor R_{AA} of D mesons in central Pb-Pb collisions is shown in Fig. 2 [14]. The left panel shows the measurements for three D-meson species, D$^+$, D^0, and D^{*+}, while the right panel shows the average values of these

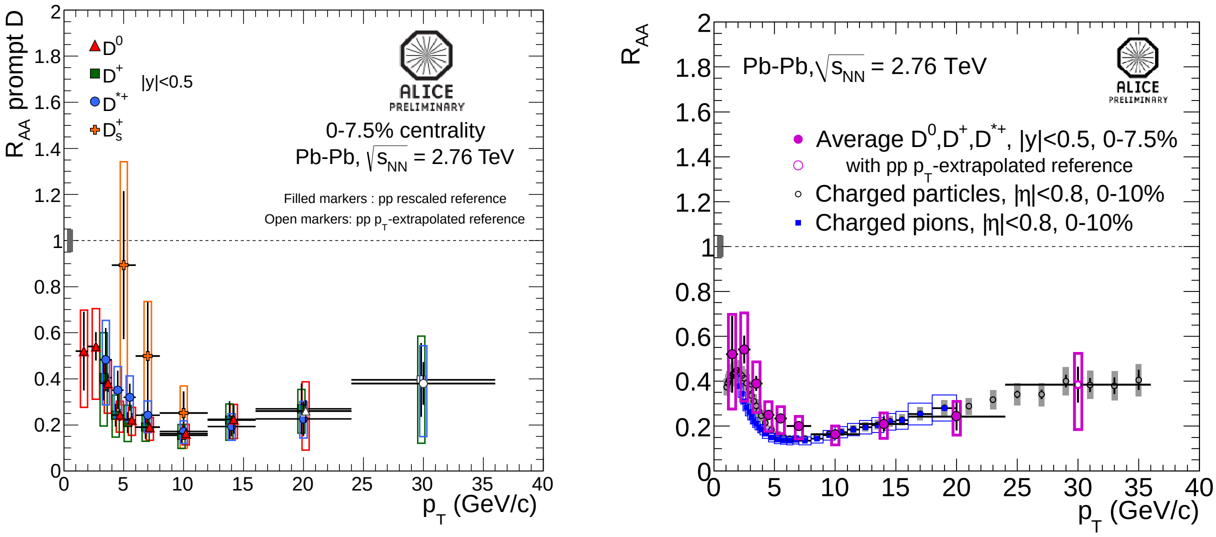

Figure 2. The transverse momentum dependence of the nuclear modification factor of prompt D mesons (particles and antiparticles) in central (0-7.5% centrality) Pb–Pb collisions (left panel). The right panel shows the average values of R_{AA} for D^+, D^0, and D^{*+} meson species in comparison to data for all charged particles and for charged pions (for 0-10% centrality).

species in comparison to data for all charged particles and for charged pions (which are for 0-10% centrality). The similar R_{AA} values of D mesons and of pions (or charged particles), well below unity, indicate that the energy loss of charm quarks is of similar magnitude compared to that of lighter quarks or gluons. The first measurement of R_{AA} for D_s mesons in heavy-ion collisions [16] is also shown in Fig. 2 (left panel). In the highest measured p_{T} bin (8-12 GeV/c), the R_{AA} for D_s mesons is compatible with that of non-strange charmed mesons. At lower p_{T}, the R_{AA} of D_s mesons seems to increase, but with the current statistical and systematic uncertainties no conclusion can be drawn on the expected enhancement of $\mathrm{D}_s$mesons with respect to non-strange D mesons [17].

The transverse momentum dependence of the elliptic flow coefficient v_2 of charmed mesons [14] is shown in Fig. 3 together with that of inclusive charged hadrons for the centrality interval 30-50%. Despite the large uncertainties, the challenging measurement of v_2 for D mesons shows a significant anisotropy, suggesting that charm quarks may take part in the collective motion built up at the quark level in the deconfined stage.

The R_{AA} and v_2 results are confronted with model predictions in Fig. 4. The theoretical models [18, 19, 20, 21, 22, 23, 24] implement parton energy loss via elastic (collisional) and radiative mechanisms. The models are able to describe the features of the data, but a quantitative description of both energy loss and elliptic flow remains challenging for all models. As noted in [24], an increase of R_{AA} as a function of p_{T} is generic for a constant fractional parton energy loss and for a parton spectrum of power-law form, with the power exponent increasing as a function of p_{T}.

A further challenge for theory is the consistent description of energy loss for light [25] and heavy quarks [13], illustrated in Fig. 5 (left panel). Partonic energy loss models achieve a good description at high p_{T} while the low p_{T} region is not described well. The data suggest $R^{D}_{\mathrm{AA}} > R^{\pi}_{\mathrm{AA}}$, as expected. Further hints on the quark flavor dependence of the nuclear modification factor are given in Fig. 5 (right panel) for intermediate p_{T} values (where the R_{AA} values exhibit a shallow minimum, see Fig. 4). The ALICE data on light flavors [25] and charmed

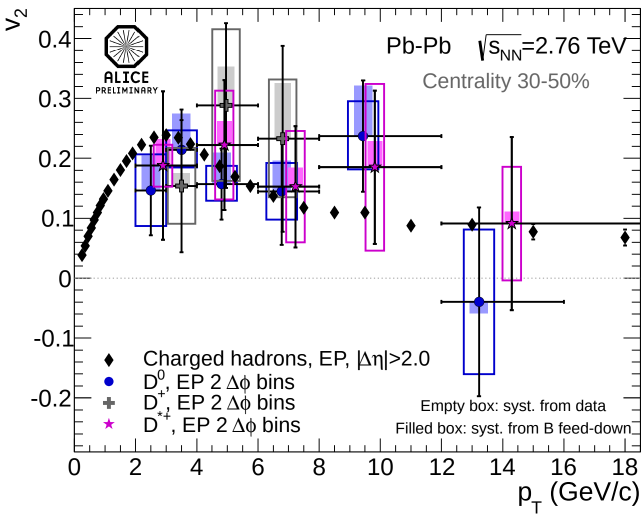

Figure 3. The transverse momentum dependence of the elliptic flow coefficient v_2 of charmed mesons for the centrality interval 30-50%. The data for inclusive charged hadrons is included for comparison.

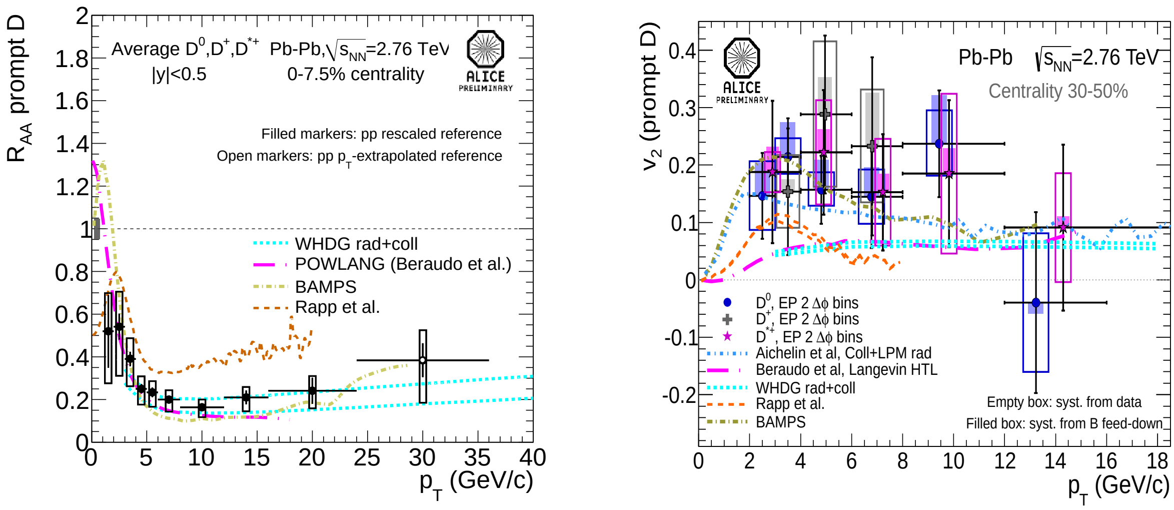

Figure 4. Transverse momentum dependence of R_{AA} (left panel, central collisions) and v_2 (right panel, 30-50% centrality) of D mesons. The mesurements are compared to model predictions (see text).

hadrons [14] are compared to the measurements of primordial J/ψ and J/ψ from decays of B hadrons [26]. Although the details of such a comparison need to be carefully considered [24], the data suggest the expected hierarchy of flavor dependence of in-medium parton energy loss. A further challenge to theory is the extraction of the heavy quark (momentum) diffusion coefficient, a quantity which was recently calculated within lattice QCD [27].

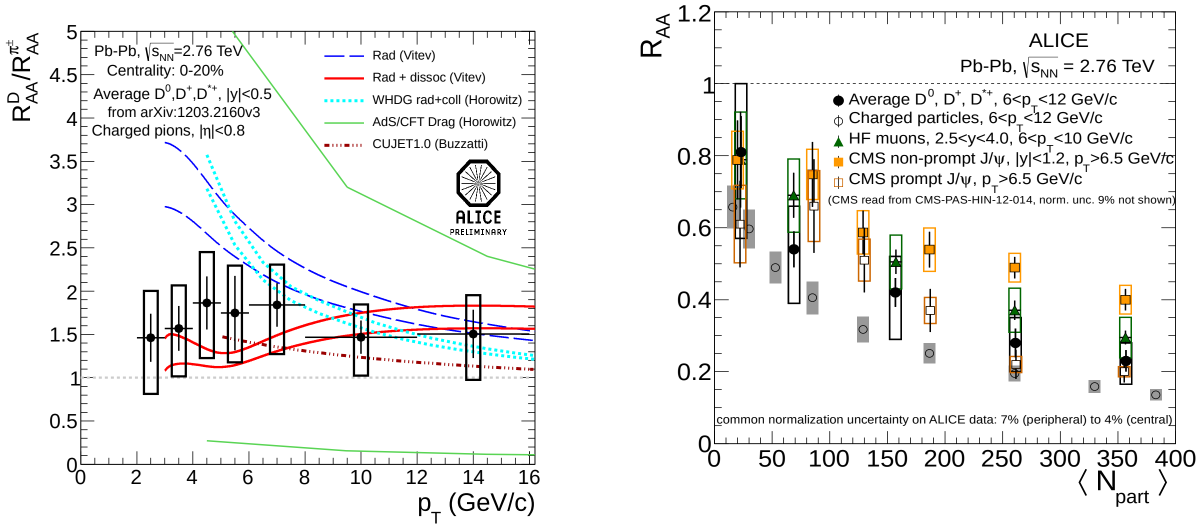

Figure 5. Left panel: transverse momentum dependence of the ratio of $R_{\rm AA}$ of D mesons and pions, data and model predictions. Right panel: centrality dependence of $R_{\rm AA}$ for hadrons carrying light and heavy quarks (see text).

3. Quarkonium

Among the various suggested probes of deconfinement, charmonium plays a distinctive role. It is the first hadron for which a clear mechanism of suppression in the QGP was proposed early on, based on the color analogue of Debye screening [28] (see [29] for a recent review). A suppression compared to pp collisions was observed in pA collisions [30], which was understood as a destruction of the pre-resonant $c\bar{c}$ state by the nucleons of the colliding nuclei. The measurements in Pb-Pb at the SPS ($\sqrt{s_{\rm NN}}$ = 17.3 GeV) [31] and in Au-Au at RHIC [32] demonstrated an "anomalous" suppression, attributed to the dense and hot QCD matter. The theoretical interpretation was a sequential suppression [33, 34] of various charmonium states as a function of energy density (temperature) of the QGP. In this picture, the J/ψ meson survives in the QGP and only the contribution from the $\psi(2S)$ and χ_c charmonium states (leading to about 10% and 30% of the total J/ψ yield, respectively) vanishes as a consequence of the melting of $\psi(2S)$ and $\chi_{c1,2}$ states. As appealing as this interpretation is, it was questioned by the non-zero $\psi(2S)$ yield measured at the SPS [35] and also later by the re-evaluation of cold nuclear matter suppression derived from p-A measurements [30].

The $\psi(2S)$ yield relative to the yield of J/ψ was noted earlier [36, 37] to correspond, for central collisions, to the chemical freeze-out temperature derived from fits to other hadron abundances. This led to the idea of statistical hadronization of charm quarks in nucleus-nucleus collisions [37]. In this model, the charm quarks produced in initial hard collisions thermalize in the QGP and are "distributed" into hadrons at chemical freeze-out. All charmonium states are assumed to be fully melted (or, more precisely, not formed at all) in the QGP and produced, together with all other hadrons, exclusively at chemical freeze-out. This model [38, 39] (see also a recent review [40]) has gained support from experimental data at RHIC [32, 41]. The model predicted a notably different pattern of J/ψ production at the LHC. Depending on the charm production cross section, even an enhanced production relative to pp collisions could be expected at the LHC in central Pb–Pb collisions [39] (see [42] for further predictions). The statistical model predicted [43] an energy-independent relative production ratio $\psi(2S)$/J/ψ about 4 times smaller in (central) AA collisions compared to pp.

Proposed at the same time as the statistical hadronization model, the idea of kinetic

recombination of charm and anti-charm quarks in the QGP [44] is an alternative quarkonium production mechanism. In this model (see [45, 46] for recent results), a continuous dissociation and regeneration of charmonium takes place in the QGP over its entire lifetime. Besides the charm production cross section, this model has as input parameters the time dependence of the temperature of the fireball as well as relevant cross sections and assumptions on the melting scenarios of charmonium states. Important observables, like the transverse momentum dependence of production yields and of elliptic flow can be calculated within the transport (kinetic) models. It predicted a rather small J/ψ regeneration component at RHIC and a sizable one at the LHC.

The measurement of J/ψ production in Pb-Pb collisions at the LHC was expected to provide a definitive answer on the question of (re)generation. The first data, measured at high-p_T by ATLAS [47] and CMS [48], showed a pronounced suppression with respect to pp collisions. Subsequently, it was seen that this J/ψ suppression is of the same magnitude as that of open-charm hadrons [13], as shown above (Fig. 4, right panel). This may indicate that the high-p_T charm quarks that form either D or J/ψ mesons had the same dynamics including a thermalization stage and a late hadronization.

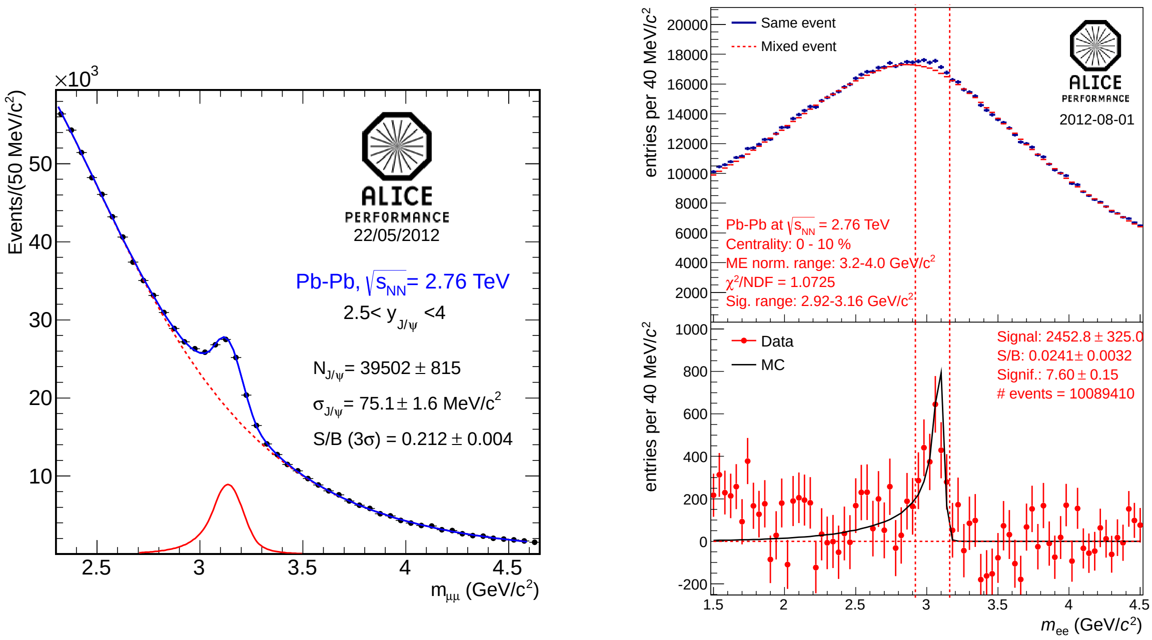

Figure 6. Invariant mass distributions measured for the $\mu^+\mu^-$ channel (Muon Spectrometer, 2.5< y <4, right panel; the dashed line is a fit to the background) and e^+e^- channel (Central Barrel, $|y|$ <0.9, right panel; the lower panel is the signal obtained after the mixed-event background subtraction, with the line the signal form obtained from Monte Carlo simulations).

Quarkonium is measured in ALICE via its dielectron channel at midrapidity and via the dimuon channel at forward rapidity, respectively, as shown in Fig. 6 (see [49, 50] for the details of the analysis). A clear difference to the RHIC results [32, 41] was seen in the first LHC measurement of the overall (inclusive in p_T) production, performed in ALICE [49]. In this case, where low p_T J/ψ production is dominant, less nuclear suppression (larger R_AA value) is seen at the LHC both at forward rapidity [51] and at mid-rapidity [52], as shown in Fig. 7. Corroborated with the CMS data [48], teh result indicates an enhanced production of J/ψ at low-p_T compared to high p_T.

At the LHC, the estimated energy density is at least a factor of 3 larger than at RHIC [53], leading to an initial temperature most likely above the one required for J/ψ dissociation. Therefore, one can conclude that the production mechanism of J/ψ and charmonium in general at the LHC is determined (to a large extent) by regeneration in QGP or by generation at chemical freeze-out.

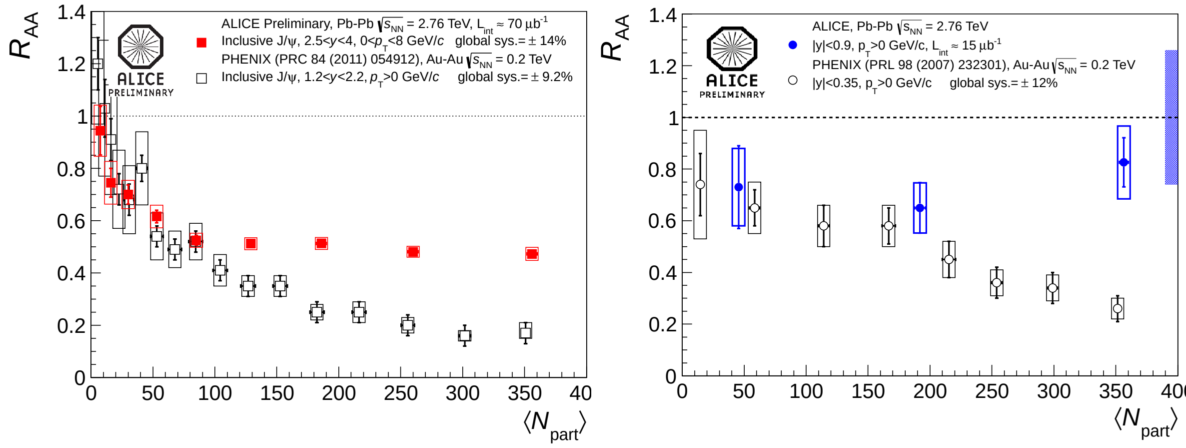

Figure 7. Centrality dependence of the nuclear modification factor for inclusive J/ψ production. The ALICE measurement (preliminary) at the LHC is compared to the PHENIX data at RHIC. The two panels show the data at forward rapidity (left) and at mid-rapidity (right).

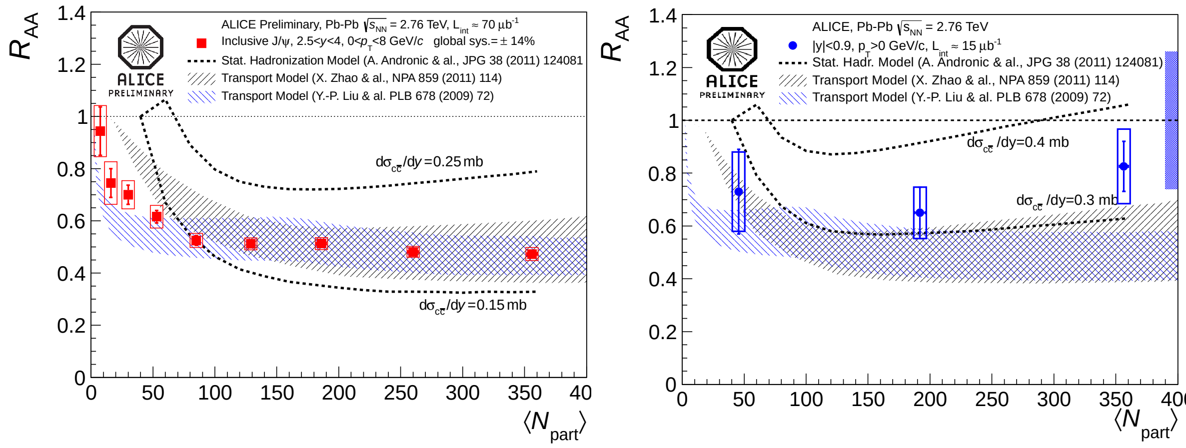

Figure 8. Centrality dependence of the nuclear modification factor for J/ψ at all momenta in comparison to theoretical models, for forward rapidity (left panel) and mid-rapidity (right panel).

Indeed, both the statistical hadronization [42] and transport [45, 46] models reproduce the data [49], as seen in Fig. 8. Based on these observations, the J/ψ production can be considered a probe of QGP as initially proposed [28], but may not be a "thermometer" of the medium [34]. Within the statistical model, the charmonium states become probes of the phase boundary between QGP and hadron phase. This extends with a heavy quark the family of quarks employed for the determination of the hadronization temperature (via the conjectured connection to the chemical freeze-out temperature extracted from fits of statistical model calculations to hadron abundances).

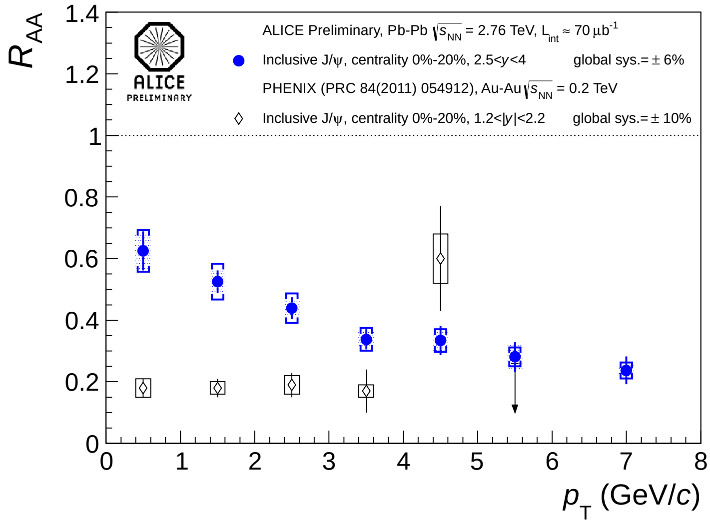

Figure 9. . Transverse momentum dependence of the nuclear modification factor for J/ψ at forward rapidity for the centrality range 0-20%. The preliminary ALICE data at the LHC are compared to measurements at RHIC by PHENIX.

The transverse momentum dependence of the nuclear modification factor, shown in Fig. 9, is, at the LHC, dramatically different than the one measured at RHIC. At low-p_T the nuclear suppression is significantly reduced (i.e. larger R_{AA}) at the LHC [51] compared to RHIC [32]. Transport model calculations reproduce the data quantitatively, as can be seen in Fig. 10 (with model of ref. [46]; the open bands represent the yield due to regeneration). In current models [45, 46], about half of the low-p_T J/ψ yield in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is produced by the recombination of charm quarks in QGP, while the rest is due to primordial production.

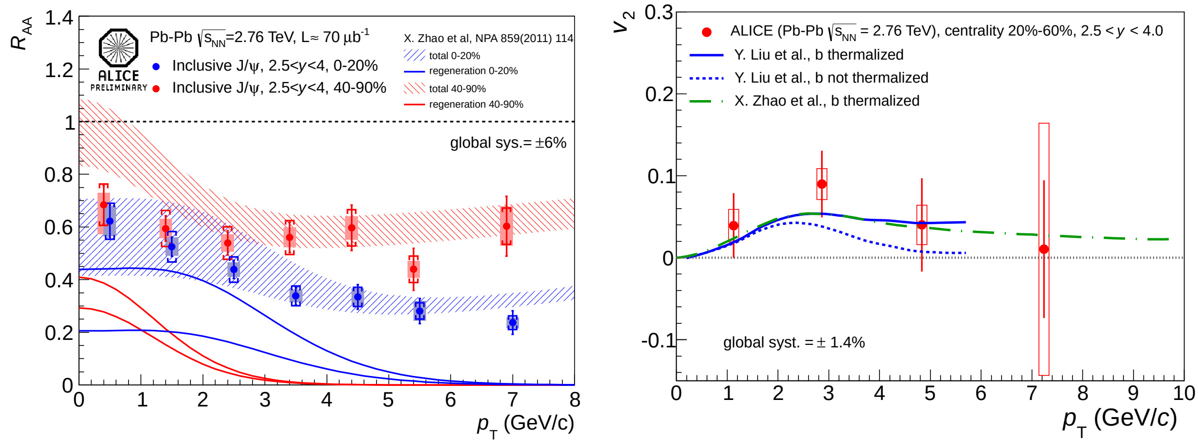

Figure 10. Nuclear modification factor (left panel, for centrality ranges 0-20% and 40-90%) and elliptic flow (right panel, for centrality range 20-60%) of J/ψ mesons as a function of transverse momentum. The ALICE data is compared with parton transport model predictions.

Both the kinetic and the statistical hadronization models require thermalization of the charm quarks in QGP. As a consequence they will follow the collective behavior of the bulk QGP and their flow will be reflected in that of charmed hadrons and quarkonia. Indeed, elliptic flow of J/ψ at LHC energies was predicted within a transport model [45]. The first measurement at

the LHC [54], shown in Fig. 10 (right), provides a tantalizing hint of a non-zero elliptic flow of J/ψ (the significance of non-zero flow for the centrality range 20-60% is 2.3σ in the p_{T} range 2-4 GeV/c). The preliminary ALICE data is consistent with the expectation from transport models, but precision data is needed in order to be able to extract information on the QGP properties and on the amount of J/ψ produced via regeneration.

The picture outlined above for the charmonium production, extracted by comparison of data and model predictions, remains to be tested by precision measurements at the LHC, which will place further constraints to models. A generic feature expected within (re)generation models is an increase of R_{AA} at the higher energy ($\sqrt{s_{\mathrm{NN}}}$ = 5.1 TeV) of collisions expected in the LHC after the current shutdown period. In particular, both the statistical and the transport models employ as input parameter the $c\bar{c}$ production cross section $\sigma_{c\bar{c}}$. The sensitivity of the calculations to $\sigma_{c\bar{c}}$ is rather large (see Fig. 8). A precision measurement of $\sigma_{c\bar{c}}$ in Pb-Pb collisions, within reach with the proposed ALICE upgrade [55], will place an important constraint to models. A precision measurement of excited states of charmonium, in particular of $\psi(2S)$, for which current data [56] are rather imprecise, could allow to discriminate between the regeneration [46] and statistical production [43] mechanisms.

4. Summary and outlook

A wealth of data has been measured by ALICE on charmed hadrons and charmonium in Pb-Pb collisions at the LHC. Parton energy loss is strong also for charm quarks and its quantitative description together with the observed elliptic flow in theoretical models remains a challenge. Charmonium exhibits features of production via regeneration in the hot deconfined medium or via statistical hadronization at the phase boundary. Disentangling these two pictures is the next challenge for the experiments and theory.

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